U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

AD-A034 210

LIFT AND DRAG EFFECTS DUE TO POLYMER INJECTIONS ON THE SURFACE OF SYMMETRIC HYDROFOILS

HYDRONAUTICS, INCORPORATED, LAUREL, MARYLAND

OCTOBER 1976

013015

ADA034210

Approved for public release; distr[illegible]on unlimited

HYDRONAUTICS, incorporated

research in hydrodynamics

Research, consulting, and advanced engineering in the fields of NAVAL and INDUSTRIAL HYDRODYNAMICS. Offices and Laboratory in the Washington, D. C., area: Pindell School Road, Howard County, Laurel, Md.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report 7603-1	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Lift and Drag Effects due to Polymer Injections on the Surface of Symmetric Hydrofoils		5. TYPE OF REPORT & PERIOD COVERED Technical Report
		6. PERFORMING ORG. REPORT NUMBER TR 7603-1
7. AUTHOR(s) Abbas M. Sinnarwalla and T. R. Sundaram		8. CONTRACT OR GRANT NUMBER(s) N00014-71-C-0063
9. PERFORMING ORGANIZATION NAME AND ADDRESS HYDRONAUTICS, Incorporated 7210 Pindell School Road Laurel, Maryland 20810		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 062-325
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research (Code 438) Department of the Navy Arlington, Virginia 22217		12. REPORT DATE October 1976
		13. NUMBER OF PAGES 47
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Polymer Additives
Pressure Distributions
Lift Effects
Drag Effects
Hydrofoil

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experimental results are presented for the effects on the lift and drag on symmetrical hydrofoils due to the injection of dilute polymer solutions on to their surfaces. Results are presented for three different polymers, namely, Polyox, Polyacrylamide and Jaguar; for purposes of comparison, results are also presented for water injection. The results indicate that while, in general, polymer injection leads to a reduction in drag, the lift can either increase or decrease depending on the polymer, the angle of attack,

20. Continued.

the surface on which the injection is made, the chordwise location at which injection is made and the injection velocity. Results for the effects of the injections on the pressure distributions on the hydrofoil are also presented, and these results are consistent with the force measurements. Tests on the effects of simultaneous injections from several chordwise locations indicate that significant reductions in drag can be achieved by a judicious choice of the locations.

HYDRONAUTICS, INCORPORATED

TECHNICAL REPORT 7603-1

LIFT AND DRAG EFFECTS DUE TO POLYMER INJECTIONS ON THE SURFACE OF SYMMETRIC HYDROFOILS

By

A. M. Sinnarwalla
and
T. R. Sundaram

October 1976

Prepared for

Office of Naval Research
Department of the Navy

Under

Contract No. N00014-71-C-0063,
NR062-325, Mod. No. P00005

i(A)

TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

Experimental results are presented for the effects on the lift and drag on symmetrical hydrofoils due to the injection of dilute polymer solutions on to their surfaces. Results are presented for three different polymers, namely, Polyox, Polyacrylamide and Jaguar; for purposes of comparison, results are also presented for water injection. The results indicate that while, in general, polymer injection leads to a reduction in drag, the lift can either increase or decrease depending on the polymer, the angle of attack, the surface on which the injection is made, the chordwise location at which injection is made and the injection velocity. Results for the effects of the injections on the pressure distributions on the hydrofoil are also presented, and these results are consistent with the force measurements. Tests on the effects of simultaneous injections from several chordwise locations indicate that significant reductions in drag can be achieved by a judicious choice of the locations.

I. INTRODUCTION

Significant research has been devoted to lift effects associated with the drag-reducing polymers since Wu's discovery of pump effects in 1969[1]. Some of the research has involved tests on propellers[2,3], finite span hydrofoils[4], circular cylinders[5] and two-dimensional hydrofoils[6] in homogeneous polymer solutions. Other research has involved tests on hydrofoils with polymer injection on the foil surface[7-11], as might actually be used in practice.

HYDRONAUTICS, Incorporated has been carrying out research on Macromolecular Solutions (Hydrodynamics of Dispersed Systems) for the Office of Naval Research, Fluid Dynamics Branch (Code 438) since 1963. During the last three years, the research program has been aimed at the investigation of the "lift effects" associated with the injection of drag-reducing fluids into the turbulent boundary layer of two-dimensional hydrofoils. The past research included the lift, drag and pressure distribution measurements on a 10-cm chord NACA 63_4-020 two-dimensional hydrofoil and the lift and drag measurement on a 20-cm chord NACA 63_4-010 two-dimensional hydrofoil with and without a polymer (200 ppm of Polyox WSR 301) injection, see References 8-10.

One rather surprising result of our early studies[8-10] was that while polymer injection on the foil surface always led to a drag reduction, under certain conditions this was accompanied by an <u>increase</u> in the lift. The above result is, of course, quite unlike that when the hydrofoil is tested in a fluid containing a small amount of polymer (the so-called "polymer ocean" case), where a drag reduction is always accompanied by a lift decrease.

Based on the belief that a successful explanation of the observed phenomena required a detailed examination of the changes

in the pressure distributions on the hydrofoil, some preliminary measurements were undertaken last year (see Reference 10 for a description of the tests and their results). Indeed, based on the experimental results, it was possible to arrive at some specific, though preliminary, conclusions. For example, Fruman, Tulin and Liu[10] concluded that the observed lift increases could not be explained in terms of changes in the boundary-layer-separation point, since the pressure distributions revealed that injection did not significantly alter the pressure distributions in the trailing-edge region. These authors argued that the observed lift effect may not be directly related to the drag-reduction phenomena and that the former may be due to a visco-elastic effect.

One direct method of examining wherher visco-elastic effects are responsible for the observed changes is to conduct tests with different polymers of differing visco-elastic behavior under otherwise identical experimental conditions. The performance of such tests was a principal objective of the present study. Specifically, the objective was to make detailed force and pressure-distribution measurements with the 10-cm chord hydrofoil with the injection of three different polymers (Polyox, Polyacrylamide and Jaguar) at two chordwise locations (10% and 30% chord).

A secondary objective of the program was to make lift and drag measurements on the 20-cm chord hydrofoil to determine the effects of simultaneous injections at several chordwise locations. Specifically, it was desired to determine whether the combined effect of simultaneous injections from several injection ports was less than, equal to, or greater than the numerical sum of the drag reduction resulting from separate injections from each of the ports. This question is, of course, of obvious practical value. Additional ports at 5% and 30% chordwise locations were provided on the 20-cm chord hydrofoil and tests were conducted for various combinations of injections of Polyox from the 5, 10 and 30% chordwise

locations.

The experimental procedure used in the present tests is described in detail in Section II of the report. The test results are presented in Section III and their significance is discussed in Section IV. Finally, some concluding remarks and recommendations are given in Section V.

II. EXPERIMENTAL PROGRAM

II.1 HSC Test Plan and Setup

As described in Section I, the objective of the proposed program was to investigate (1) the effects of different polymers on lift, drag and pressure distributions of a 10-cm chord two-dimensional hydrofoil, and (2) the effect of several drag-reducing injections of a polymer on the lift and drag of a 20-cm chord two-dimensional hydrofoil. Accordingly, the following High Speed Channel Test Program was adapted:

1. Perform lift, drag and pressure measurements on a 10-cm chord hydrofoil under the following test conditions:

   a. Injected Fluid: Water, 200 ppm Polyox WSR 301 (Union Carbide), 350 ppm Polyacrylamide (Polyscience - Cat. #2806) and 1500 ppm Jaguar WPB (Stein, Hall and Co., Control #23-0548) solutions.

   b. Injection velocity: $V_i/V_f = 0.1$ and 0.3, where V_f = free stream velocity (11 meters/sec).

   c. Angle of Attack: $0°$, $2.5°$ (or $3.25°$) and $5°$.

   d. Injection Side: Suction (top) and pressure (bottom) sides.

   e. Injection Position: 10% and 30% chord.

2. Perform lift and drag measurements on a 20-cm chord hydrofoil under the following test conditions:

   a. Injection Fluid: Water and 200 ppm Polyox WSR 301 solution.

   b. Injection Velocity: $V_i/V_f = 0.1$, where V_f = 11 meters/sec.

c. Angle of Attack: 0°, 2.5° and 4°.

d. Injection Side: Suction Side.

e. Injection Position: Various combinations of 5, 10 and 30% chord positions.

All the tests were performed in the HYDRONAUTICS High Speed Channel (HSC) modified to obtain a two-dimensional flow. The detailed description of the channel modification, the hydrofoils and the design of the injection slits is given in References 8 and 10. The 10-cm chord hydrofoil has two injection slits, one on each side of the foil, and located at 10% and 30% chord lengths from the leading edge. The 20-cm chord hydrofoil, which previously had only one injection slit at 10% chord length, was modified so as to have a total of 3 slits at 5, 10 and 30% chord lengths on the same side of the hydrofoil. The opening of the 5 and 30% chord slits, however, was 0.0127 cm—half that of the 10% chord slit.

The injected fluid was contained in a seven-gallon reservoir, which was pressurized so as to drive the fluid into the injection slits through a regulating valve and a flowmeter. Three sets of regulating valves and flow meters were used so as to have an independent control on the injection through various slits of the 20-cm chord hydrofoil. The flowmeters were calibrated with water only, as independent checks with polymer solutions did not show any significant effect on the calibration.

The polymer solutions used were 200 ppm Polyox WSR 301 (Union Carbide), 350 ppm Polyacrylamide (Polyscience - Cat. #2806), and 1500 ppm Jaguar WPB (Stein, Hall and Co., Control #23-0548). The description of the rationale for the selection of the specific polymer concentration chosen appears in the following subsection II.2.

II.2 Selection of Polymer Concentrations

A series of pipe-flow tests were conducted to obtain the drag-reduction-versus-concentration characteristics of the above polymers at a Reynolds number corresponding to the velocity at which the HSC tests were performed. The test setup (Figure 1) consists of measuring the pressure drop across a given length of the test section when the polymer solution of known concentration flows through the test pipe. A detailed description of the procedure appears in Reference 12.

Test results are shown in Figure 2. For a flat plate, Fruman and Tulin[13] give the following empirical equation* relating the injected concentration, C_i , to the trailing edge concentration, C_ℓ:

$$C_\ell = 10.79 \left(\frac{V_i}{V_f}\right)^{1.74} \left(\frac{s}{\ell}\right)^{1.16} C_i^{2.16} \qquad [1]$$

where

V_i is the injection velocity,
V_f is the free stream velocity,
s is the slit opening, and
ℓ is the flat plate length aft of the injection slit.

In the HSC tests, using the above relation, the polymer concentrations at the injection ports were so chosen as to maintain the concentrations of the polymers over the entire hydrofoil in the range corresponding to the maximum drag reduction. The chosen values of C_i, i.e., 200, 350 and 1500 ppm for Polyox, Polyacrylamide, and Jaguar, respectively, were calculated for the case $V_i/V_f = 0.1$ and $s/\ell = 0.0014$ corresponding to 10% chord slit; however, these chosen values of C_i were also used for $V_i/V_f = 0.3$ and 30% chord injection cases.

*It should be noted that this equation was derived from experimental results for Polyox injection; as such, its use for other polymers may be questionable. Nevertheless, its use is necessary since a rational alternative does not exist.

II.3 Lift, Drag and Pressure Measurement Techniques

The lift and drag forces were measured by means of four reluctance-type block gauges attached to the foils as shown in Figure 3. The total lift and drag load capacities of these gauges were 100 and 30 pounds, respectively. Each surface of the 10 cm chord hydrofoil has ten 1.01-mm diameter pressure taps between 18 to 86 percent chord length of the foil. These pressure taps are arranged diagonally at an angle of 52 degrees to the stream so as to minimize the downstream influence of each on the others. The pressures were measured by means of three diaphragm pressure transducers (Pace Engineering Co.), coupled to a scanner, Scanivalve Model WSG-12. Each of the two 10 psi capacity transducers measured the pressure on each side of the foil, while the third 5-psi transducer measured the pressure differential between the two sides of the foil. The free-stream velocity in the channel was measured by a 10-psi capacity pressure transducer associated with the pitot static probe. All the force gauges and pressure transducers were calibrated prior to the tests. The electrical output signals from the gauges and transducers, integrated over a four-second period, were observed on a digital voltmeter and the values were printed out by an on-line teletype.

II.4 Accuracy and Repeatability of the Tests

A detailed analysis on the accuracy and repeatability of the tests, given in References 8 and 10, has shown that the lift and drag coefficients were reproducible within a variation range of ±2 percent. This question has been further investigated during the present research phase. In order to eliminate possible errors and to increase the degree of confidence in the results, the following test procedure was followed throughout the test program. Before any injection test, the specified hydrofoil incidence angle

was set and the free-stream velocity of 11 meters/sec was established in the high speed channel. This velocity was continuously monitored throughout the test. After establishing the velocity, a first-series of measurements was performed of the velocity and the lift and drag forces integrated over a four-second period. The fluid was then injected and upon stabilization of the lift and drag voltmeters, the second-series of measurements was performed. The injection was then discontinued and again upon stabilization of the voltmerers, a third series of "no-injection" measurements was carried out. During the experiments conducted to measure the pressure distribution (all the tests with 10-cm chord hydrofoil), the above test procedure was repeated for each of the 10 pairs of pressure taps. Hence, for these tests, each of the velocity, lift and drag measurements is an average of the 10 individual measurements. The standard deviations for the velocity and the lift-drag measurements for no-injection, as well as injection cases, are less than 0.2 and 1 percent, respectively.

The pressure gauges were checked for proper operation by comparing the difference between the pressures measured with two of the gauges against the pressure differential of the third gauge. Figure 4 shows the agreement between both measurements for the no-injection case with foil angle of 5 degrees and velocity of 11 meters/sec. Also shown in this figure is the ΔC_p computed for an inviscid and unbounded flow using the procedure given in Reference 14. The significant differences in the calculated and measured pressure distributions near the trailing edge of the hydrofoil are, as discussed in Section IV, attributed to boundary-layer effect. However, it should again be noted that the repeatability of the measurements of the changes in the lift, drag and the pressure distribution due to a fluid injection is more important than the absolute values themselves. As will be shown in

Section IV, the changes in the normal forces due to polymer injection as measured by the force gauges are in very good agreement with those values computed from the relative change in the pressure distribution around the hydrofoil.

The hydrodynamic characteristics of the foil were insensitive to the buildup of Polyox and Polyacrylamide concentrations in the recirculating water as this buildup was never allowed to exceed 1 ppm and, moreover, the solution degraded when circulated through the 1000 HP centrifugal pump of the high speed channel. In the case of Jaguar solution, however, the drag on the foil increased slightly with time. As the changes in the force and pressure measurements due to polymer injection are relative to the averages of the immediately preceding and following no-injection measurements, the polymer-buildup effect even in this case is negligibly small. Thus, it would seem from the above discussion that the velocity, force and pressure measurements are well within the range of unavoidable experimental errors.

III. PRESENTATION OF THE RESULTS

All the HSC tests were performed at a free-stream velocity, V_f, of 11 meters/sec. The results of the lift, drag and pressure measurements on the 10-cm chord hydrofoil are given in Figures 5 to 11, while the results of the lift and drag measurements on the 20-cm chord hydrofoil are given in Figure 12.

A. 10-cm Chord Hydrofoil

Figures 5 and 6 show the effect of 10% chord injection of water and polymers on the drag and lift coefficients, respectively, as a function of foil angle and ratio of injection velocity to free-stream velocity, V_i/V_f. Changes in the lift coefficients for polymer injections relative to the water injection case are shown in Figure 7.

A general observation of these figures reveals that:

1. Water injection results in a drag increase, or at most a slight drag reduction; whereas polymer injection always results in a drag reduction.

2. Except for the Polyox injection at $V_i/V_f = 0.3$ rate, polymer injection on the bottom (pressure) side results in a larger drag reduction than when the injection is on the top (suction) side, and this difference in the drag reduction increases with the foil angle.

3. Water injection on the suction side results in a lift decrease; whereas that on the pressure side results in a lift increase. The magnitude of this lift change, however, is larger for $V_i/V_f = 0.3$ rate.

4. Relative to the water injection case, polymer injection on the suction side increases the lift, while that on the pressure side decreases the lift except for the case of Polyox injection at

$V_i/V_f = 0.3$ rate. The magnitude of this lift change, however, is larger for $V_i/V_f = 0.3$ rate in the case of Jaguar injection and for $V_i/V_f = 0.1$ rate in the cases of Polyox and Polyacrylamide injections.

The results on the effect of 30% chord injection of water and polymers on the drag and lift measurements are given in Figures 8 to 10. These results show that:

1. Water injection results in a drag increase, or at most a slight drag reduction; whereas a polymer injection always results in a drag reduction.

2. Injection of Polyox at $V_i/V_f = 0.1$ and 0.3, and that of Polyacrylamide at $V_i/V_f = 0.3$ show similar results as that for a 10% chord Polyox injection at $V_i/V_f = 0.3$.

3. As compared to the 10% chord injection results, the suction side injection of polymers (relative to water injection case) results in a smaller increase or even a decrease in the lift, while the pressure side injection of polymers results in a smaller decrease or even an increase in the lift.

The change in the chordwise pressure distribution due to suction-side injections of Polyox and Jaguar at a foil angle of 2.5° is plotted in Figure 11. The hydrofoil has pressure taps only between 18 and 86% of its chord length; nevertheless, the general trend is good enough to make the following observations:

1. Polyox injections on the top (suction) side at $V_i/V_f = 0.1$ results in a pressure decrease on the most of the suction side and in a pressure increase on the pressure side; hence, one would expect a lift increase. On the other hand, Polyox injection at $V_i/V_f = 0.3$ results in a pressure increase on most of the suction side and in a pressure decrease on the pressure side; hence, one would expect a lift decrease.

2. Jaguar injection on the top (suction) side at $V_i/V_f = 0.1$ as well as at 0.3 rate results in a pressure decrease on the suction side and in a pressure increase on the pressure side; hence, a lift increase is expected in both cases. However, the magnitudes of this pressure change on both sides are comparatively larger for $V_i/V_f = 0.3$; hence, a relatively larger increase in the lift is expected for that case.

A detailed discussion of these results is given in Section IV.

B. 20-cm Chord Hydrofoil

The second part of the test program was to investigate the effect of water and Polyox injections through various combinations of injection positions on the lift and the drag of a 20-cm chord hydrofoil. The following observations can be made from the test results shown in Figure 12.

1. Drag reduction due to water injection is less than 2%.

2. 10% chord injection of Polyox gives higher drag reduction than 5 or 30% chord injection. It should, however, be mentioned here that the opening of the 5 and 30% chord slits is 0.0127 cm, while that of the 10% chord slit is 0.0254 cm.

3. Polyox injection through more than one slit results in a higher drag reduction than the injection through a single slit, and at 0 degree foil angle, the drag reduction achieved is more than 20% when injection is made through all three slits simultaneously.

4. The lift decrease due to water injection or an increase due to Polyox injection is only a few percent for foil angles greater than 1 degree.

5. Comparison between the results of 10 cm and 20 cm chord hydrofoils under identical test conditions (Polyox concentration = 200 ppm, $V_i/V_f = 0.1$, slit position at 10% chord having the same

slit opening/chord length ratio) shows lower percent drag reduction but higher percent lift increase for the 10-cm chord hydrofoil.

A detailed discussion of these results is given in Section IV.

IV. DISCUSSION OF THE RESULTS

As pointed out earlier, our early studies[8,9] indicated that, under certain conditions, polymer injection not only leads to drag decrease but also to a lift increase, so that significant increases in the lift/drag ratio could be realized. In general, it was found that a lift increase accompanied a drag decrease when the polymer injection was on the suction side of the hydrofoil, and that both drag and lift decreased when the polymer injection was on the pressure side of the hydrofoil.

In an attempt to understand the phenomenology responsible for the observed lift behavior, tests[10] were undertaken to measure the pressure distributions on the hydrofoil for the cases with and without polymer injection. These preliminary tests indicated that polymer injection on one surface (suction or pressure) of the hydrofoil changes the pressure distribution on <u>both</u> surfaces, though the effect is more pronounced on the surface on which the injection is made. It was also found that the pressure distributions are consistent with the lift forces measured by the block gauges; that is, the forces obtained by integrating the measured pressure distribution were the same, within accepted experimental error, as those measured by the block gauges.

Based on the observations described above, Fruman, Tulin and Liu[10] examined several possible explanations for the observed behavior. A change in boundary-layer separation behavior was discounted as a feasible explanation, since the measured pressure distributions do not display any evidence of this (the major pressure changes occur immediately aft of the slit rather than near the trailing edge). These authors then considered boundary-layer thinning on the side on which the injection is made as a possible explanation. The decreased boundary-layer thickness at the trailing edge of the hydrofoil can be directly related to the drag

reduction, since the change in the momentum flux in the wake must equal the change in drag. In turn, the reduced thickness of the boundary layer at the trailing edge on the side on which the injection is made can be related to a change in the effective angle of attack. It is relevant to note that, according to the above explanation, injection on the pressure side will lead to a decrease in the trailing-edge boundary-layer thickness on this side and a consequent decrease in the effective angle of attack, whereas injection on the suction side will lead to the opposite effect— a result which is consistent with observed behavior.

Fruman, Tulin and Liu calaculated the reduction in trailing-edge boundary-layer thickness using the measured drag reduction and calculated the change in lift corresponding to the change in the effective angle of attack by using the measured lift-curve slope. They found that in all but a few cases, the measured lift changes were considerably larger than those that can be predicted using the mechanism described above.

Fruman, Tulin and Liu[10] then considered viscoelastic effects as possible explanations for the observed changes. They pointed out that when the observed lift forces are plotted against the logarithm of the free stream velocity a straight-line behavior results in a manner analogous to the behavior noted in pitot-tube measurements in flows containing polymer additives. Such a plot also indicates that there is a threshold velocity below which the lift effect does not appear, the actual value of this threshold velocity being dependent on the test conditions. However, when the results are plotted in terms of the local velocity at the injection slit, a single threshold velocity results. These observations lend credence to the concept that a visco-elastic effect may be responsible for the observed lift effects. In particular, Tulin, Fruman and Liu suggest that the injected polymer flow

may enter the boundary layer in the form of a "swollen jet" and that this effect may cause the lift changes.

The objective of the present study was to explore the suggestions given above in more detail. Specifically, the principal objective was to make detailed force and pressure measurements on the 10-cm chord hydrofoil with three different polymer additives to determine the effects of visco-elastic behavior. A secondary objective was to investigate, with the 20-cm chord hydrofoil, the effects of simultaneous injections at several chordwise locations. The results of these efforts were described in some detail in Section III.

It can be seen from Figures 5, 6, 8 and 9 that the different polymers lead to significantly different results. Moreover, polymer injection yields results which are significantly different from that for water injection. For example, polymer injection always leads to a drag reduction, while water injection often leads to a drag increase or, at most, to very small drag reductions. Similarly, the lift behavior due to injection seems to be significantly different for the different polymers and for water. It can be seen from Figures 6 and 9 that water injection always seems to produce a lift force in a direction opposite to the side in which the injection is made, while the direction of the lift change due to polymer injection can be either in the same direction as that of the injection or opposite to it depending on the polymer (compare Jaguar and Polyox at 0° of attack and 30% chord injection, Figure 9), the rate of injection (compare 0.1 and 0.3 rates of injection for Polyox at 0° and 2.5° angles of attack, Figure 6), and the angle of attack (compare 0° and 2.5° with 5° for Polyox injection at 10% chord on the suction side, Figure 6).

It can be seen from Figures 5 and 8 that there are some general trends that are evident in the drag-reduction behavior and

that there is some consistency between the results for the different polymers. For example, at small angles of attack an increase in the injection velocity always seems to lead in an increase in the magnitude of drag reduction. Also, in most cases injection on the pressure side seems to lead to larger drag reduction than corresponding injections on the suction side.

On the other hand, the lift results given in Figures 6 and 9 display fewer trends and less of a consistent behavior. For example, even at zero angle of attack, increasing the injection rate of polyacrylamide at the 10% chord location leads to a decrease in the lift effect (either positive or negative), whereas increasing the injection rate at the 30% chord location leads to an increase in the lift effect.

Fruman, Tulin and Liu argue that the mechanisms governing the drag reduction and the lift effect may be fundamentally different, and demonstrate that the critical velocity for the former is an order of magnitude greater than that for the latter. The present results seem to confirm this view.

Some examples of the measured pressure distributions are shown in Figure 11, which gives the differences in the pressure coefficients with and without injections for the cases of Polyox and Jaguar. It is important to note that there are fundamental differences in the pressure distributions for the different polymers. Thus, for the case of Jaguar injection shown in Figure 11, the pressure coefficient on the bottom (pressure) side is increased, while the pressure coefficient on the top (suction) side is decreased. These changes in the pressure distribution lead to a lift increase, with changes in the pressure coefficient being larger for the larger injection velocity so that the lift increase for the latter case is also larger than that for the former. These results are, of course, consistent with the results shown in Figure 6.

On the other hand, for the case of the Polyox injection, also shown in Figure 11, for the smaller injection rate, there is an increase in the values of the pressure coefficient on the bottom side, and, in general, a decrease in the values of the pressure coefficient on the upper side; thus, there is an increase in lift due to the injection. When the injection rate is increased, the values of the pressure coefficient on the bottom are decreased and the values over most of the top surface are increased. Thus, there is a decrease in the lift. These observations are consistent with the results given in Figure 6.

It is relevant to point out here that in all, eighty detailed pressure distributions have been measured, and that the qualitative behavior of the forces (that is, lift increase and decrease) which can be deduced from these measurements compare well with the behavior of the forces that are directly measured by the block gauges. Such a comparison is shown in Figure 13, which shows the pressure distributions for 10% chord, topside injection of Polyox at an angle of attack of 5°. In the figure, the distributions have been extrapolated in the regions (close to the leading and trailing edges) where there are no pressure taps. It can be seen that the total-force coefficients obtained by integrating the pressure distributions (ΔC_{L_p}) are the same, within accepted experimental errors, as the measured lift values ($\Delta C_{L'}$). These comparisons lend credence to the self-consistency of the data.

One important feature of the pressure distributions that is worthy of special attention is the sharp decrease in the pressure coefficient some distance aft of the injection position. This sharp negative peak in the pressure distribution is a characteristic feature of most of the cases considered, and always occurs on the same side on which the injection is made. The magnitude and chordwise extent of this peak have an important bearing on the

magnitude as well as direction of the net lift force that results due to the polymer injection. Thus, it is our view that seeking a rational explanation for the occurrence of this peak is a necessary prerequisite to the development of a theoretical framework for explaining the observed lift effects.

As mentioned earlier, Fruman, Tulin and Liu[10] have suggested that the lift effect of polymer injection may be due to the fact that the polymer stream enters the flow around the hydrofoil in the form of a "swollen jet" due to the visco-elastic behavior of the polymer solution. It is plausible to suppose that the observed peaks in the pressure distribution may be due to these "swollen jets". However, this conjecture does not seem to be supported by the observations, since water injection also leads peaks in the pressure distribution, as illustrated in Figure 14. In Figure 14 the changes in the pressure distributions resulting from water and Polyox injections are compared, with all other test conditions being identical (angle of attack = 0° and lower side injection at 30% chord). For the case of Polyox, there is a negative peak on the bottom-side pressure distribution (the side on which the injection is made) for both rates of injection, the magnitude of the peak being larger for the larger rate of injection. However, for the case of water injection, while there is small negative peak for the smaller rate of injection, the pressure peak becomes positive for the larger rate of injection. Thus, it is difficult to attribute the observed pressure peaks to a "swollen jet" effect.

Several other features of the pressure distributions are also of interest. In many cases, as in the case of Polyox injection illustrated in Figure 11, there are strong positive pressure regions before and following the negative pressure peaks. Also, the pressure distribution is affected everywhere on the foil surface regardless of the side or location at which injection is made.

Moreover, the actual location at which injection is made seems to have little or no influence on the location of the pressure peak, the latter apparently being influenced more by the basic nondisturbed pressure distribution on the hydrofoil.

The considerations given would seem to suggest that the observed lift effects may be due to a boundary-layer displacement effect caused by the injection, with the detailed nature of this displacement effect being dependent on the visco-elastic properties of the injected polymer. The hypothesis that the observed effects may be due to boundary-layer interaction becomes even more plausible when one compares the actual measured pressure distributions under undisturbed conditions (that is, in the absence of injection) with theoretical computations based on thin-airfoil theory; see Figure 4. In passing, it may again be noted that results from two different types of measurement are shown in Figure 4, and that the excellent agreement between the two affords considerable confidence on the accuracy of the measurements.

Figure 4 compares the measured differences in the pressure coefficients on the top and bottom sides of the hydrofoil with a theoretical calculation which neglects boundary-layer displacement effects[14]. It can be seen that there are significant differences between the calculated and measured distributions, especially near the trailing edge of the hydrofoil; these differences are typical of such comparisons, are well known in the literature (see References 15-17, for example), and are attributed to boundary-layer effects. The potential-flow streamlines around the hydrofoil are displayed outward not only due to the thickness distribution of the hydrofoil, but also due to the boundary layer on the foil surface. Hence, better results would be obtained if, in the computations, instead of using the actual hydrofoil shape, an altered shape in which the boundary-layer displacement thickness is added to the shape is used.

In general, the boundary layer on the upper surface of the hydrofoil will grow faster than that on the lower surface because of the adverse pressure gradient existing on the top surface from the minimum-pressure point onward. Therefore, the effective hydrofoil shape (that is, the actual shape plus the displacement thickness) will have a slightly turned up trailing edge at a relatively small positive angle of attack. The differences between the computational results and the measurement near the trailing edge of the foil are directly attributable to the effect mentioned above and, indeed, excellent agreement between the two results is obtained if boundary-layer displacement effects are included in the computation[16,17].

The relevance of the above remarks in the present context is that, as can be seen from Figure 4, the boundary-layer displacement effects can have a significant effect on the pressure distributions, these effects being considerably larger than the observed lift effects. Thus, even small changes in the dynamic evolution in the boundary layer on the surface on which the injection is made can be expected to produce changes in the pressure distributions of the type observed in the present experiments. In other words, the present test results suggest that the lift effect may not be due to a localized perturbation caused by the injection, but rather, may be due to a general change in the effective hydrofoil shape in the entire region downstream of the injection slit. In particular, nothing in the observed pressure distributions suggest a localized change immediately aft of the injection slit and, indeed, characteristic features such as the sharp negative peak occur at locations which are more or less independent of the location of the injection slit as well as the polymer that is injected.

The hypothesis offered above can be verified directly, since the measured pressure distributions can be analyzed using classical thin-airfoil theory, and the numerous modifications and

improvements of it that exist in the literature, so that in each case the "effective" hydrofoil shape that will produce the observed pressure distributions can be calaculated. This "effective" hydrofoil shape can then be viewed in terms of a change in the evolution of the boundary layer around the actual hydrofoil. By these means, correlations can be sought between the observed effects and the test variables in terms of the massive body of information that exists in the literature on the behavior of boundary layers under favorable and adverse pressure gradients, and on the influence on them of injections and various surface perturbations. Because of the large body of data that we have acquired under the present study, it is believed that such a method of approach is indeed likely to be fruitful.

As pointed out earlier, a secondary objective of the present test series was to investigate the effects of simultaneous injections from more than one chordwise location. Previous tests[8,9] had indicated that an increase in the injection velocity, and thus the amount of polymer introduced into the flow does not necessarily linearly increase the observed drag reduction. Indeed, beyond a certain injection velocity, further increases lead to little or no increase in drag reduction and, in some cases, actually lead to drag increases. Thus, it is of considerable practical interest to determine whether the injection of the same amount of polymer from different chordwise locations would lead to a larger effect than the injection from a single location.

Results from some tests on the 20-cm chord hydrofoil to explore the question raised above are shown in Figure 12. As with all other cases, tests were conducted with water injection as well as with polymer injection. The figure shows the results of individual injections from 5, 10 and 30% chordwise locations, as well as simultaneous injections from various combinations of these

locations. The first point to note in the figure is that, as expected, water injection has a relatively small effect on the drag as well as the lift. The second point to note is that the measured drag reductions for Polyox injection at the 10% chordwise location and a 10% injection velocity are consistent with those measured in earlier tests[8], though the latter values are slightly smaller. Note also that for single injections, the maximum drag reduction is produced, at all three angles of attack, by the injection at the 10% chordwise location, with injections at the other two locations giving significantly lower values.

Now, turning to the effects of combined injection, it can be seen from Figure 12 that simultaneous injection from the 5 and 10 percent chordwise locations produces a drag reduction which is significantly lower than the sum of the drag reductions obtained by individual injections at the two locations. Specifically, at zero-degree angle attack the drag reduction due to combined injection is only 19.5%, while the drag reduction expected on the basis of the sum of the individual cases is 25%. A similar effect is observed for injections from the 10% and 30% chordwise locations.

Results of our previous tests[8] indicate that, at zero-degree angle of attack and for injection at the 10% chordwise location, increasing the injection velocity from 10% to 20% results in an increase in the drag reduction of only about 3%. The present results show that simultaneous injection from the 10% and 30% locations leads to a similar increase over the case of the injection at 10% alone. Thus, there are no special advantages to injecting simultaneously from the 10% and 30% locations, as compared to injecting at a higher velocity from the 10% location alone. On the other hand, simultaneous injection from the 5% and 10% locations leads to a 5% increase in drag reduction compared to injection at the 10% location alone. Thus the results indicate that by

a judicious choice of injection locations, the drag-reduction effect can be increased (as compared to injection from a single location) by simultaneous injections, though the effect is less than the numerical sum of the reduction observed in the cases of separate injections from these locations.

Data on the lift behavior are also shown on Figure 12, though relatively few general observations are possible in this case. Due to fiscal constraints, it was not possible to undertake more detailed measurements on this part of the study.

V. CONCLUDING REMARKS

Tests were conducted on the 10-cm chord hydrofoil in the HYDRONAUTICS High Speed Channel with injection of three different polymers, namely, Polyox, Polyacrylamide and Jaguar. All tests were also repeated for the cases of no injection and water injection, so as to enable isolation of those effects which can be definitely attributed to polymer behavior. The test variables were injection velocity (0.1 and 0.3 times the free stream velocity), chordwise location of injection slits (10% and 30%), surface on which injection is made (suction and pressure sides) and angle of attack (0°, 2.5° and 5°). Quantities measured were lift and drag forces as well as detailed pressure distributions on both the top and bottom surfaces.

The test results show that injections of different polymers, under otherwise identical test conditions, do produce dramatically different results, thus indicating that the observed lift changes must be due, at least in part, to certain basic polymer characteristics. However, since quantities such as the polymer relaxation times were not measured, it is difficult to draw general conclusions. On the other hand, even from the tests for a single polymer, it is difficult to infer consistent trends in the observed lift behavior with respect to changes in the other test conditions such as angle of attack, injection velocity or injection position. The data are self-consistent in that the lift forces measured directly by the block gauges agree well, within the bounds of accepted experimental error, with the values deduced by integrating the measured pressure distributions.

The measured pressure distributions display several interesting features. Firstly, polymer injection at any location on either (upper or lower) surface appears to change the pressure distribution

at all locations, though the changes on the side on which injection is made are more dramatic. In particular, for all injection cases, the pressure distribution displays a sharp peak some distance downstream of the injection position, though the exact location of this pressure peak seems to be related more to the nature of the basic undisturbed pressure distribution on the foil surface and less to the actual chordwise location at which injection is made. The pressure peak always occurs on the same side on which the injection is made and for polymer injection is always negative (regardless of whether injection is on the top or bottom side), while for water injection it is often positive. Because of the first of the features mentioned above, the effect of polymer injection is to reduce the average pressure on the side on which injection is made, so that, depending on the magnitude and the spacial extent of the pressure peak, the lift is either increased or decreased regardless of whether the injection is performed on the top or bottom surface.

It is believed that the observed pressure changes may be caused by a boundary-layer displacement effect. Thus, a better understanding of the observed effects can be obtained by determining, using thin-airfoil theory, the "effective" body shape that will produce the measured pressure distributions and interpreting the changed foil shape in terms of boundary-layer displacement effects. Because of the availability of the pressure distributions for eighty different cases, we believe that meaningful correlations can be obtained; it is planned to obtain such correlations in the near future. It is also planned to correlate the observed force changes in terms of appropriate nondimensional parameters obtained through a similitude analysis.

Results from a limited test series to investigate the effects of simultaneous injection from more than one chordwise location

indicate that, by a judicious choice of the locations, significant increases in drag reduction can indeed be obtained. However, the drag reduction under simultaneous injection from several locations appear to be always less than the sum total of the drag reductions obtained when injections are made separately at each of the locations.

REFERENCES

1. Wu, Jin, "Lift Reduction in Additive Solutions," Journal of HYDRONAUTICS, Volume 3, Number 5, pp. 198-200, October 1969.

2. Kowalsky, T., "Effect of Polymer Additives on Propeller Performance," J. HYDRONAUTICS, Vol. 5, No. 1, January 1971.

3. Henderson, L. H., "Effects of Polyethlene-Oxide Solutions on the Performance of a Small Propeller," Thesis, U. S. Naval Postgraduate School, September 1971.

4. Wolf, J. H. and Cahn, R. D., "Lifting Surfaces in Polymer Solutions," NSRDC Report 3653, May 1971.

5. Sarpkaya, T., and Rainey, P. E., "Flow of Dilute Polymer Solutions about Circular Cylinders," U. S. Naval Postgraduate School, NPS-59SL1021A, February 1971.

6. Sarpkaya, T., "On the Performance of Hydrofoils in Dilute Polyox Solutions," International Conference on Drag Reduction, Cambridge, England, September 1974.

7. Lehman, A. F. and Suessmann, R. T., "An Experimental Study of the Lift and Drag of a Hydrofoil with Polymer Ejection," Oceanics, Incorporated, Report Number 72-94, November 1972.

8. Fruman, D. H., Sundaram, T. R. and Daugard, S. J., "Effect of Drag Reducing Polymer Injection on the Lift and Draf of a Two-Dimensional Hydrofoil," International Conference on Drag Reduction, Cambridge, England, September 1974.

9. Fruman, D. H., "Lift Effects Associated with Drag Reducing Polymer Injection on Two-Dimensional Hydrofoils," 1974 Annual Meeting of the Ordnance Hydroballistics Advisory Committee, Newport, Rhode Island, October 1974. Submitted for publication to the Journal of Ship Research.

10. Fruman, D. H., Tulin, M. P., and Liu, H-L., "Lift, Drag and Pressure Distribution Effects Accompanying Drag-Reducing Polymer Injection on Two-Dimensional Hydrofoil," HYDRONAUTICS, Incorporated Technical Report 7101-5, October 1975.

11. Lehman, A. F., "Additional Investigations of the Hydrodynamic Characteristics of a Hydrofoil Employing Polymer Ejection," presented at the 1975 Annual SEAHAC Meeting, Monterey, California, October 1975.

12. Fruman, D. H., and Santo, J. E., "Shear Degradation of Drag-Reducing Polymer Solutions," HYDRONAUTICS, Incorporated Technical Report 7213-2, Section 2, January 1974.

13. Fruman, D. H., and Tulin, M. P., "Diffusion of a Tangential Drag-Reducing Polymer Injection on a Flat Plate at High Reynolds Numbers," 1974 Annual Meeting of the Ordnance Hydro-ballistics Advisory Committee, Newport, Rhode Island, October 1974. Submitted for publication to the Journal of Ship Research.

14. Abbott, I. H., von Doenhoff, A. E., and Stivers, L. S., "NACA Wartime Report," ACR Number L5C05, March 1945.

15. Preston, J. H., "The Approximate Calculation of the Lift of Symmetrical Aerofoils Taking Account of the Boundary Layer, with Application to Control Problems," CR. & M. No. 1996, 1943).

16. Preston, J. H., "The Calculation of Lift Taking Account of Boundary Layer," (R&M No. 2725, 1949).

17. Sundaram, T. R., "The Calculation of the Pressure Distribution Over the Surface of a Two-Dimensional Wing Taking Account of the Boundary Layer," Master's Thesis, The Indian Institute of Science, Bangalore, India, 1960.

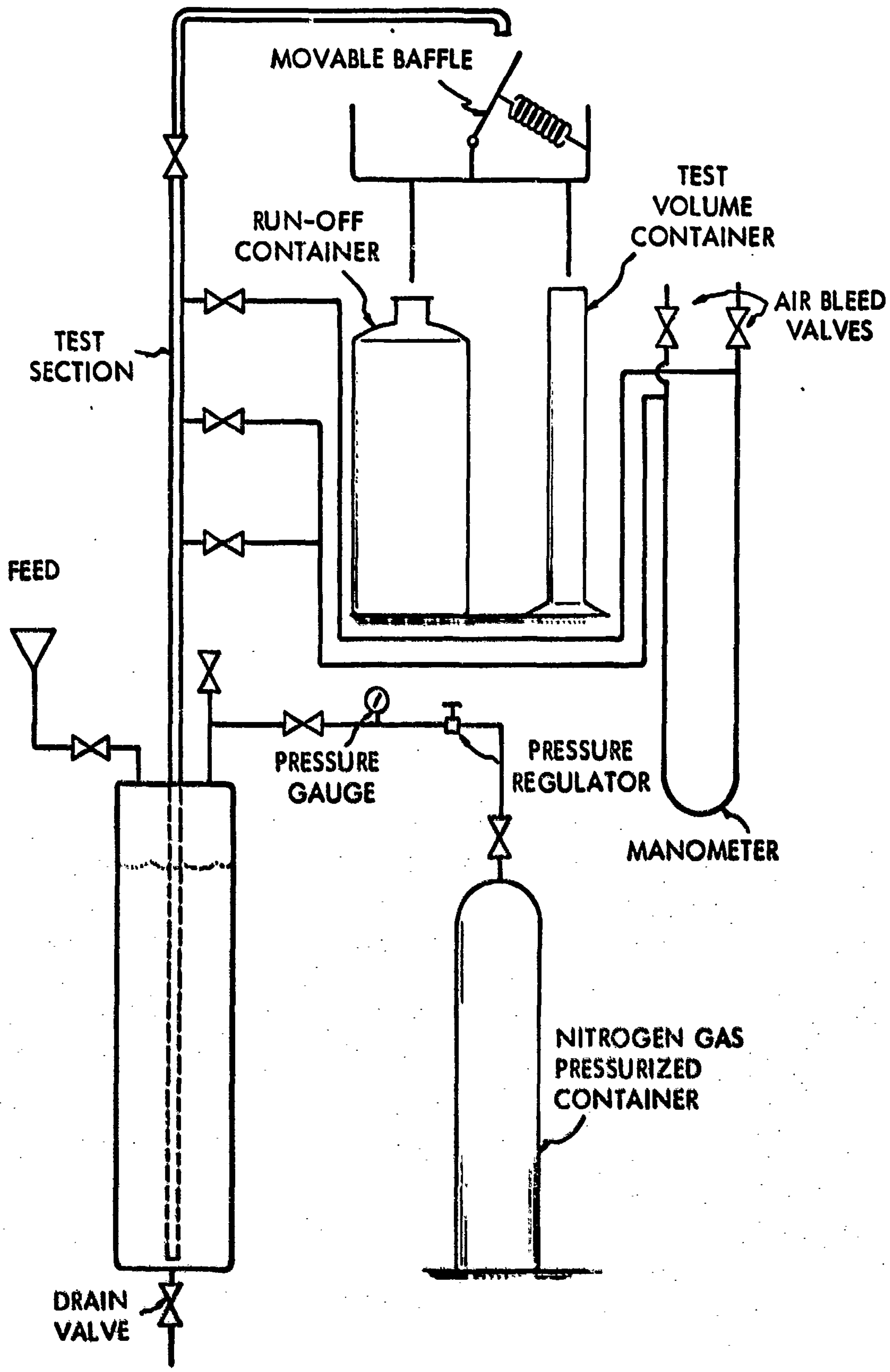

FIGURE 1 - OVERALL VIEW OF THE PIPE-FLOW TEST SYSTEM

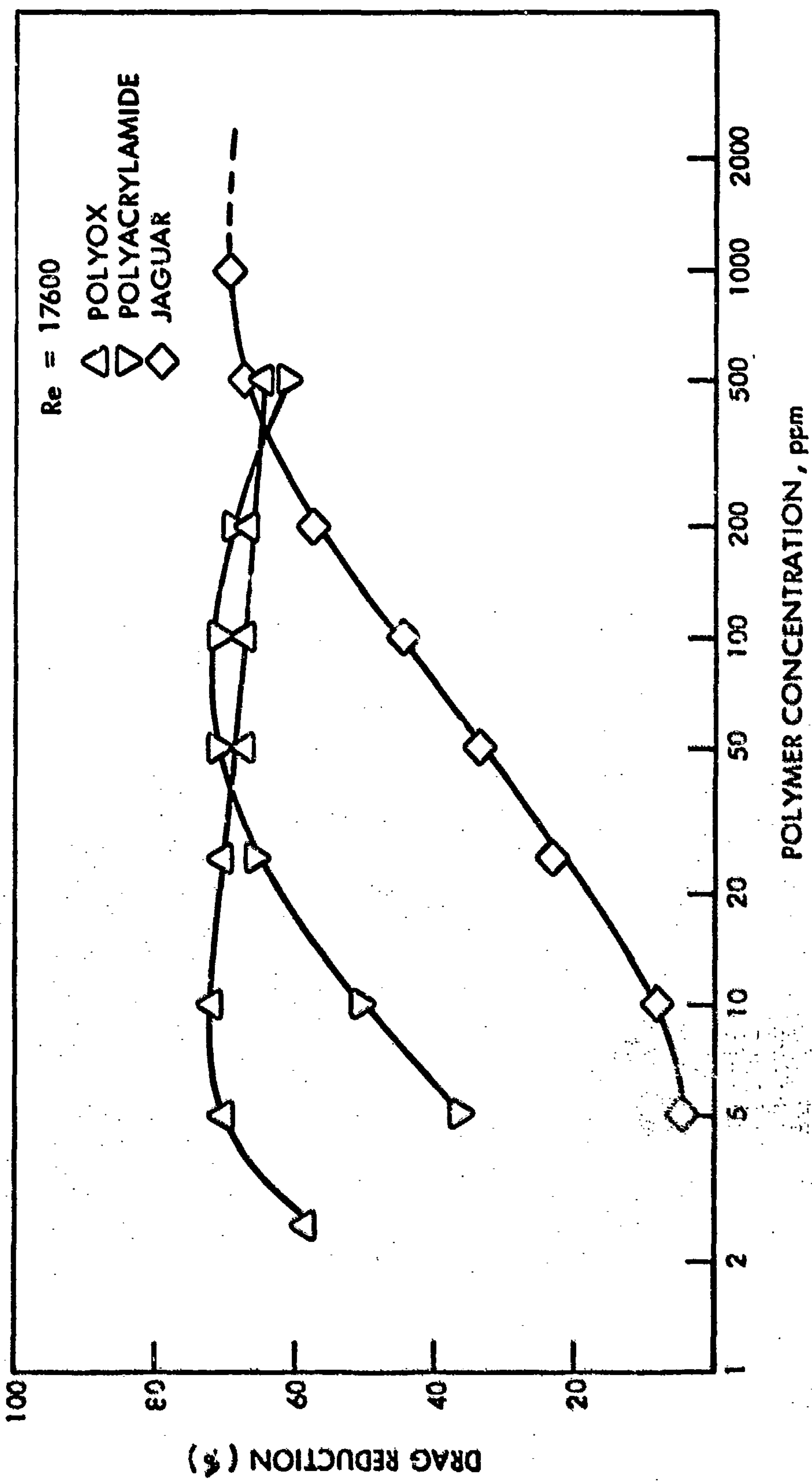

FIGURE 2 - EFFECT OF POLYMER CONCENTRATION ON THE FRICTION DRAG IN CASE OF A SMOOTH PIPE FLOW

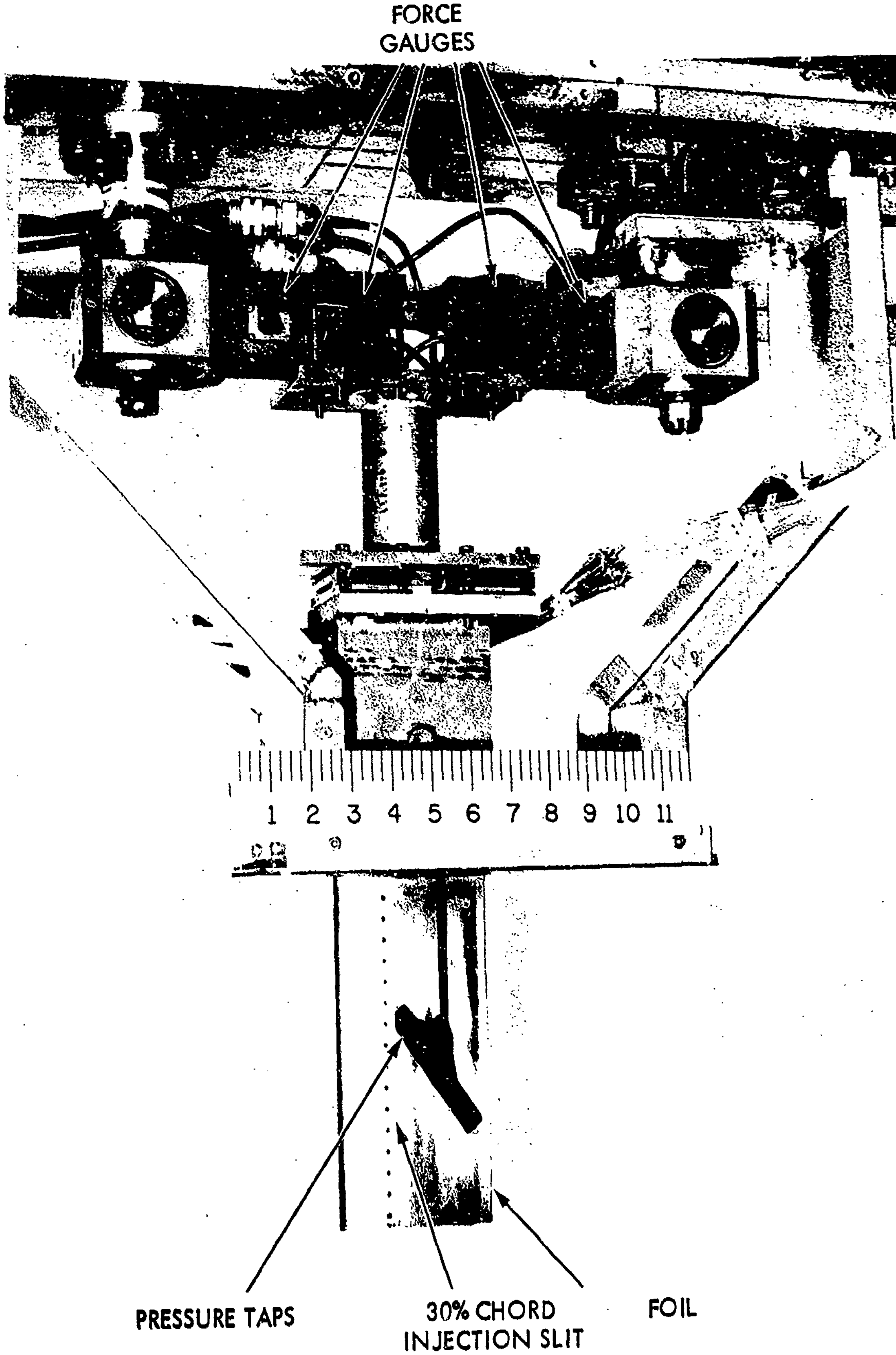

FIGURE 3 - 10-cm CHORD HYDROFOIL SHOWING FORCE GAUGES ARRANGEMENT, INJECTION SLIT, AND PRESSURE TAPS

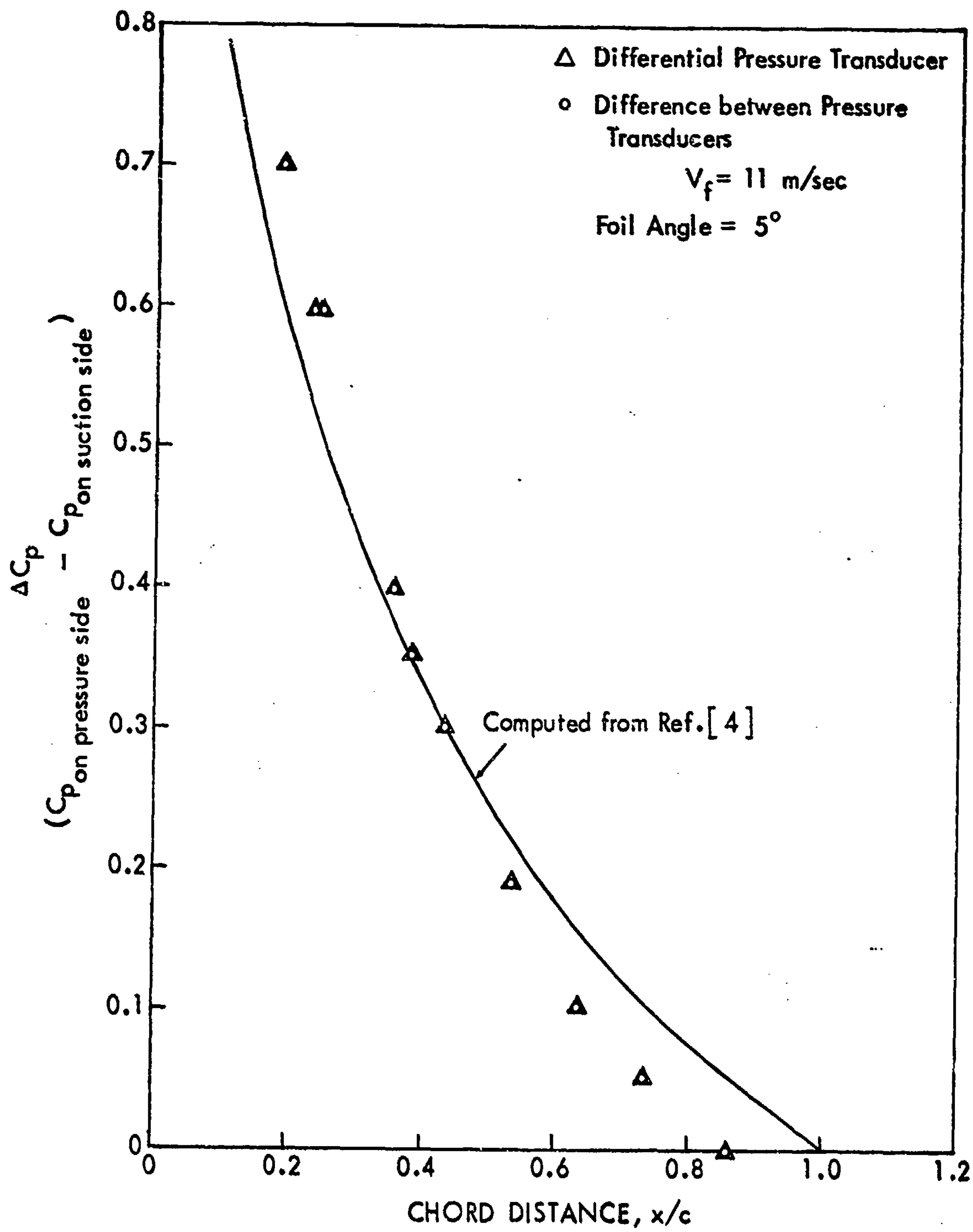

FIGURE 4 - COMPARISON BETWEEN ΔC_p VALUES MEASURED BY TWO DIFFERENT METHODS DURING A TEST WITH NO INJECTION

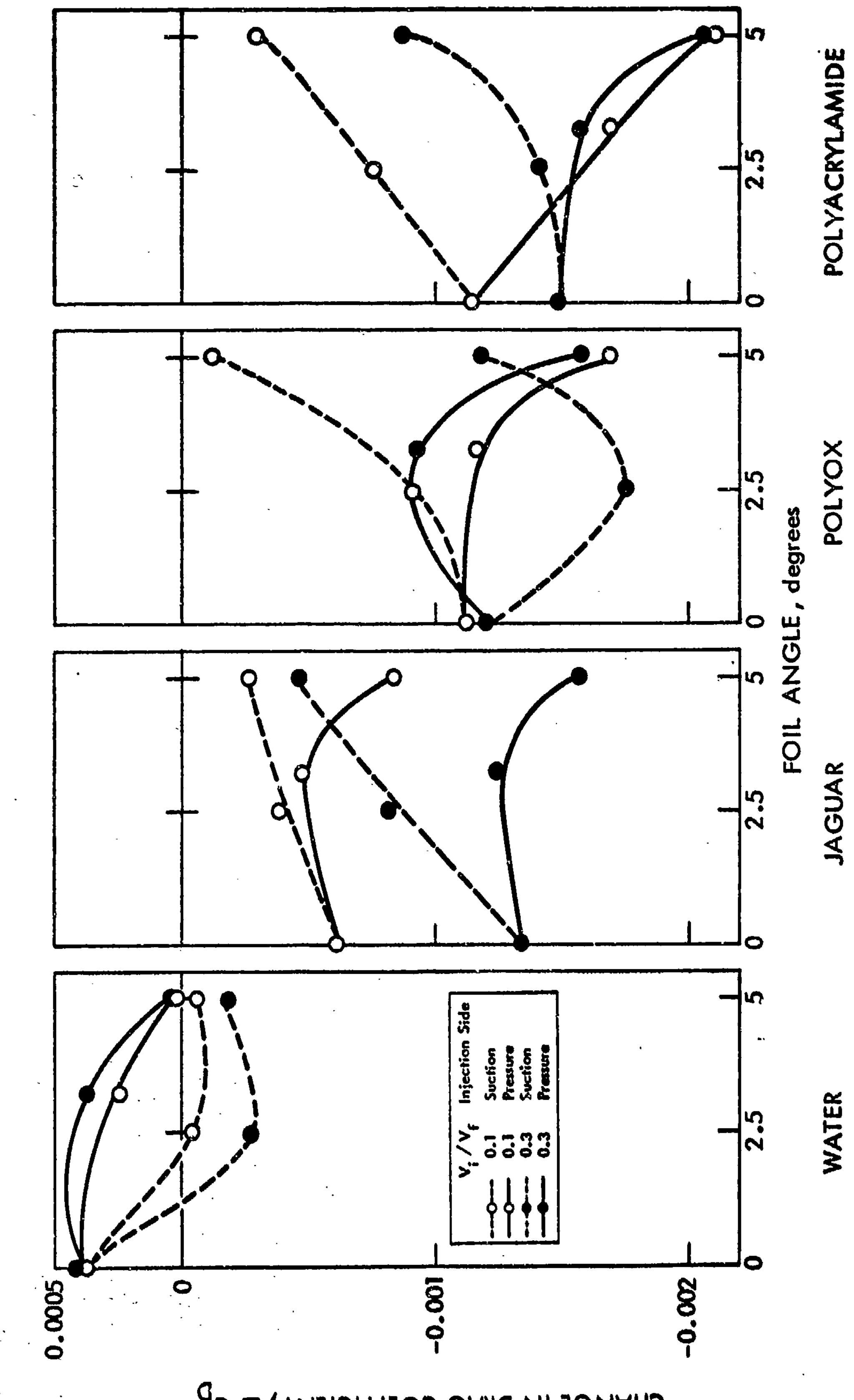

FIGURE 5 – EFFECT OF 10% CHORD INJECTION OF WATER AND POLYMERS ON THE DRAG COEFFICIENT OF A 10 cm CHORD HYDROFOIL

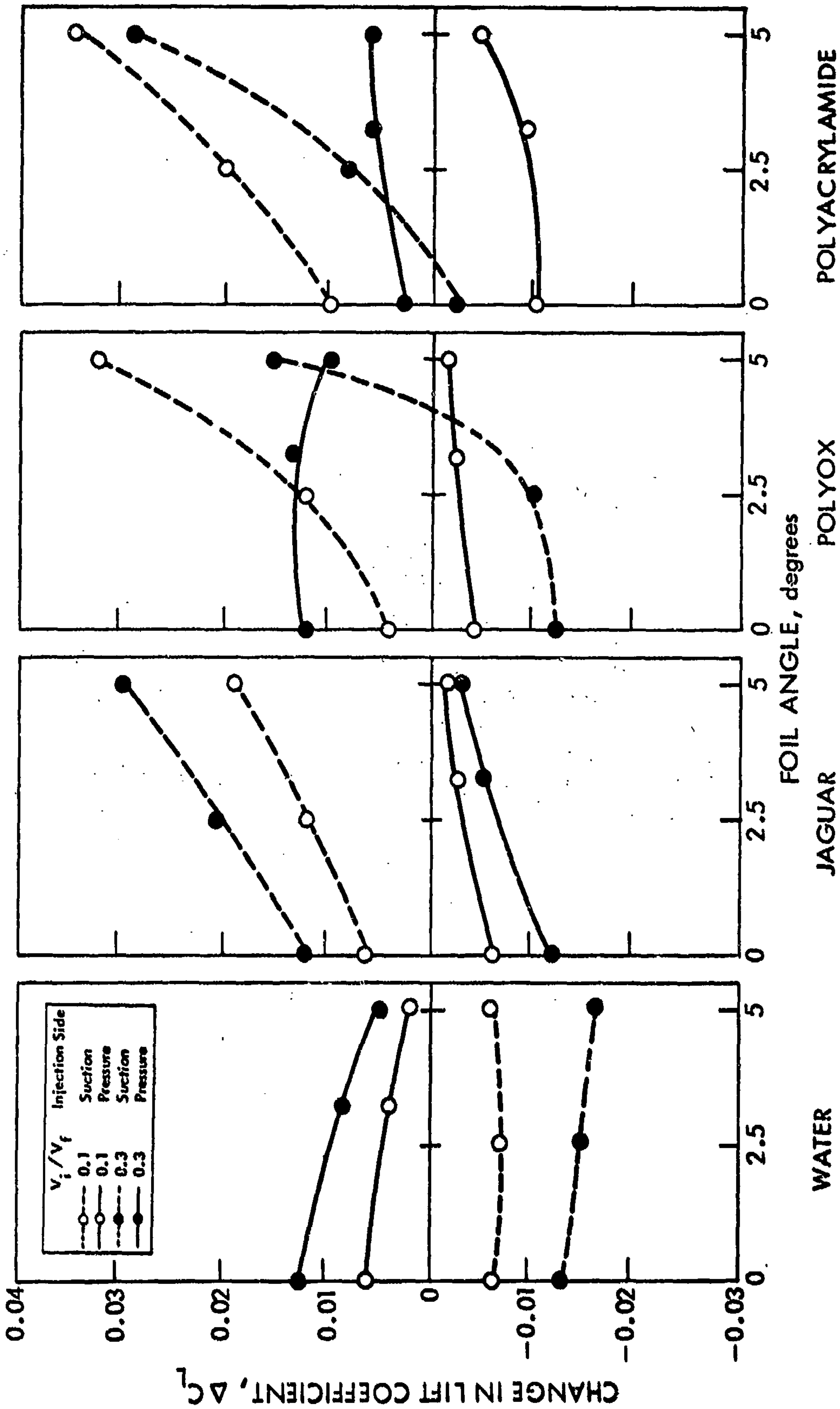

FIGURE 6 - EFFECT OF 10% CHORD INJECTION OF WATER AND POLYMERS ON THE LIFT COEFFICIENT OF A 10 cm CHORD HYDROFOIL

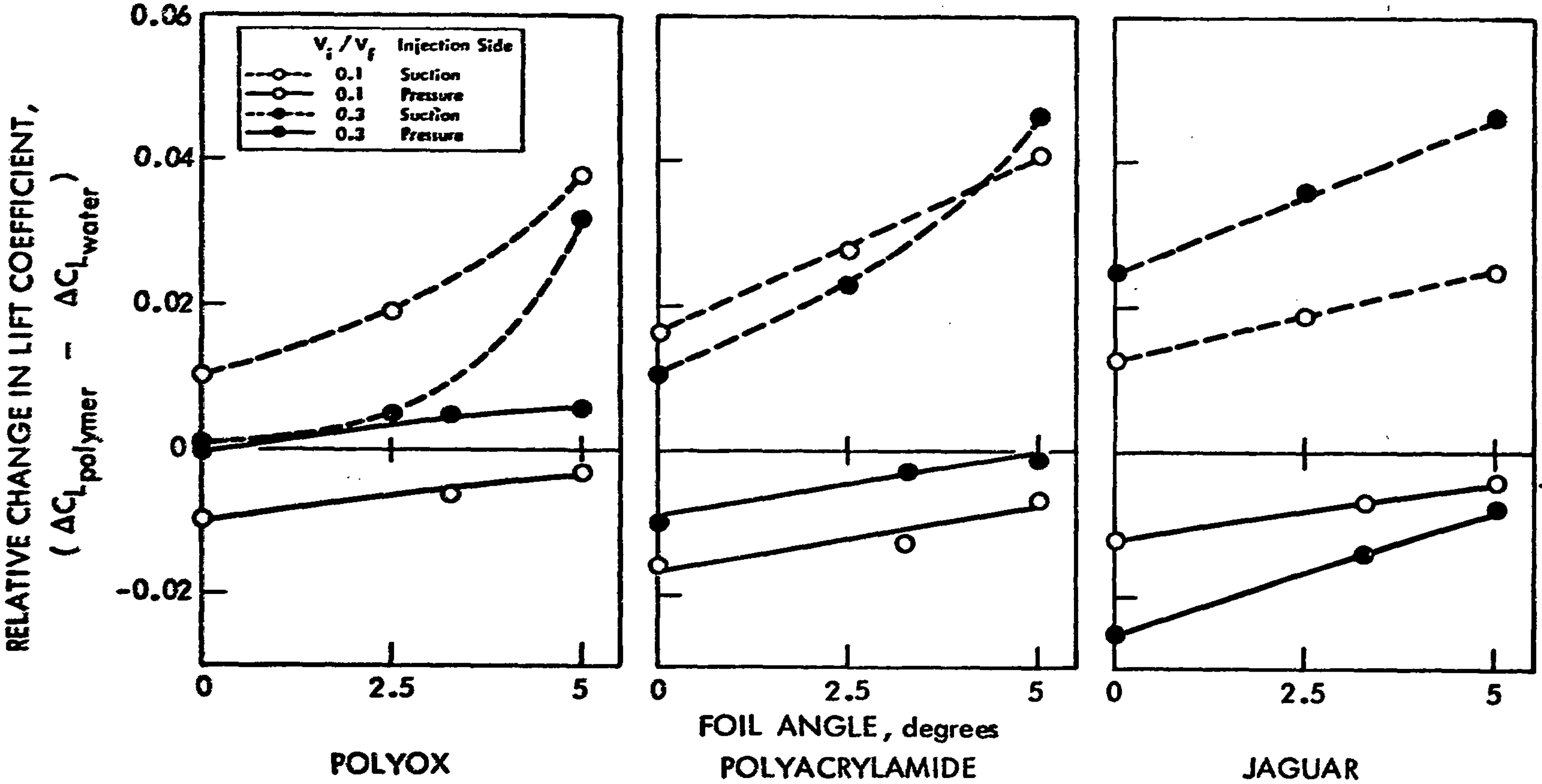

FIGURE 7 - EFFECT OF 10% CHORD INJECTION OF POLYMERS (RELATIVE TO THAT OF WATER) ON THE LIFT COEFFICIENT OF A 10 cm CHORD HYDROFOIL

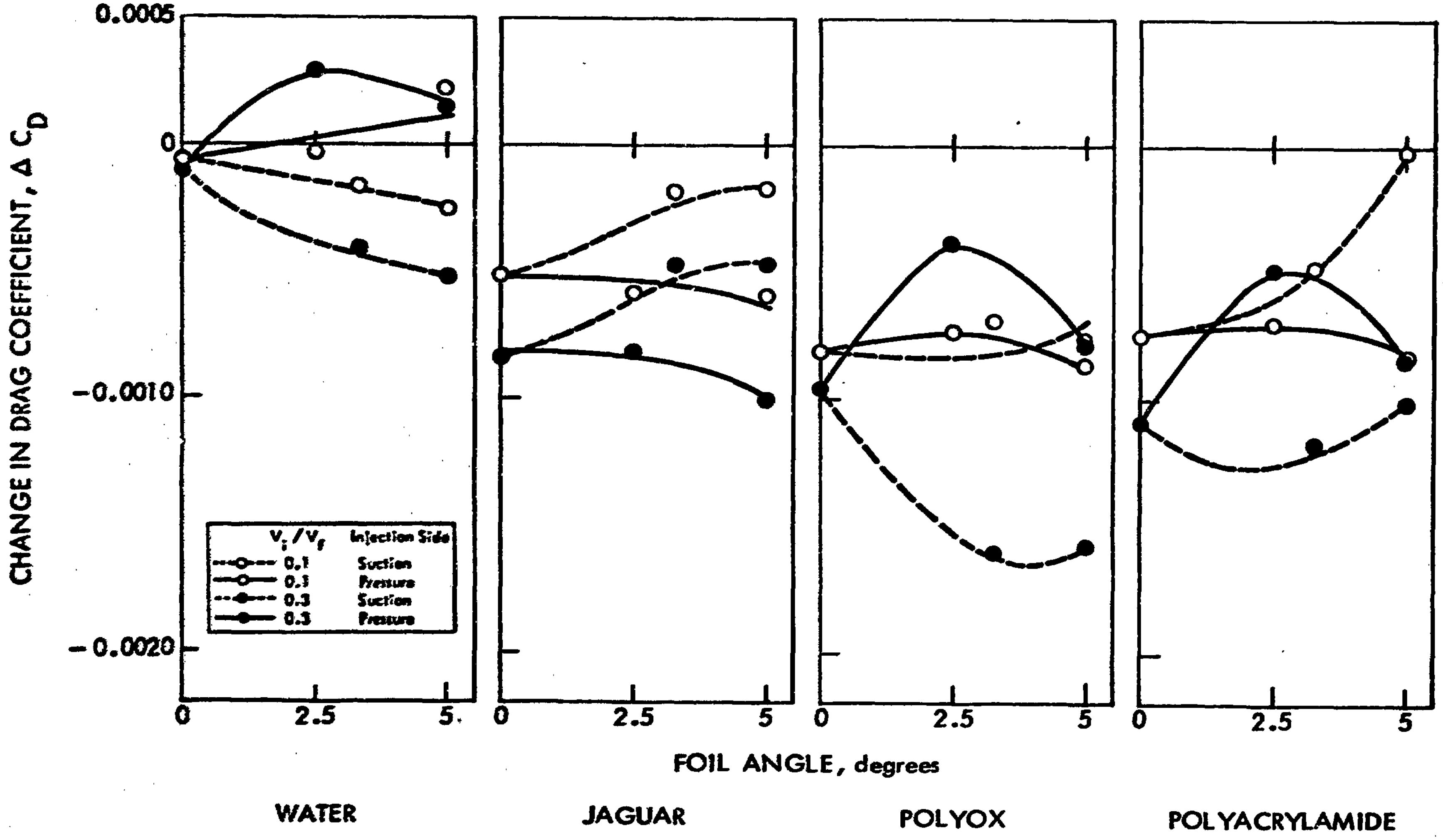

FIGURE 8 - EFFECT OF 30% CHORD INJECTION OF WATER AND POLYMERS ON THE DRAG COEFFICIENT OF A 10 cm CHORD HYDROFOIL

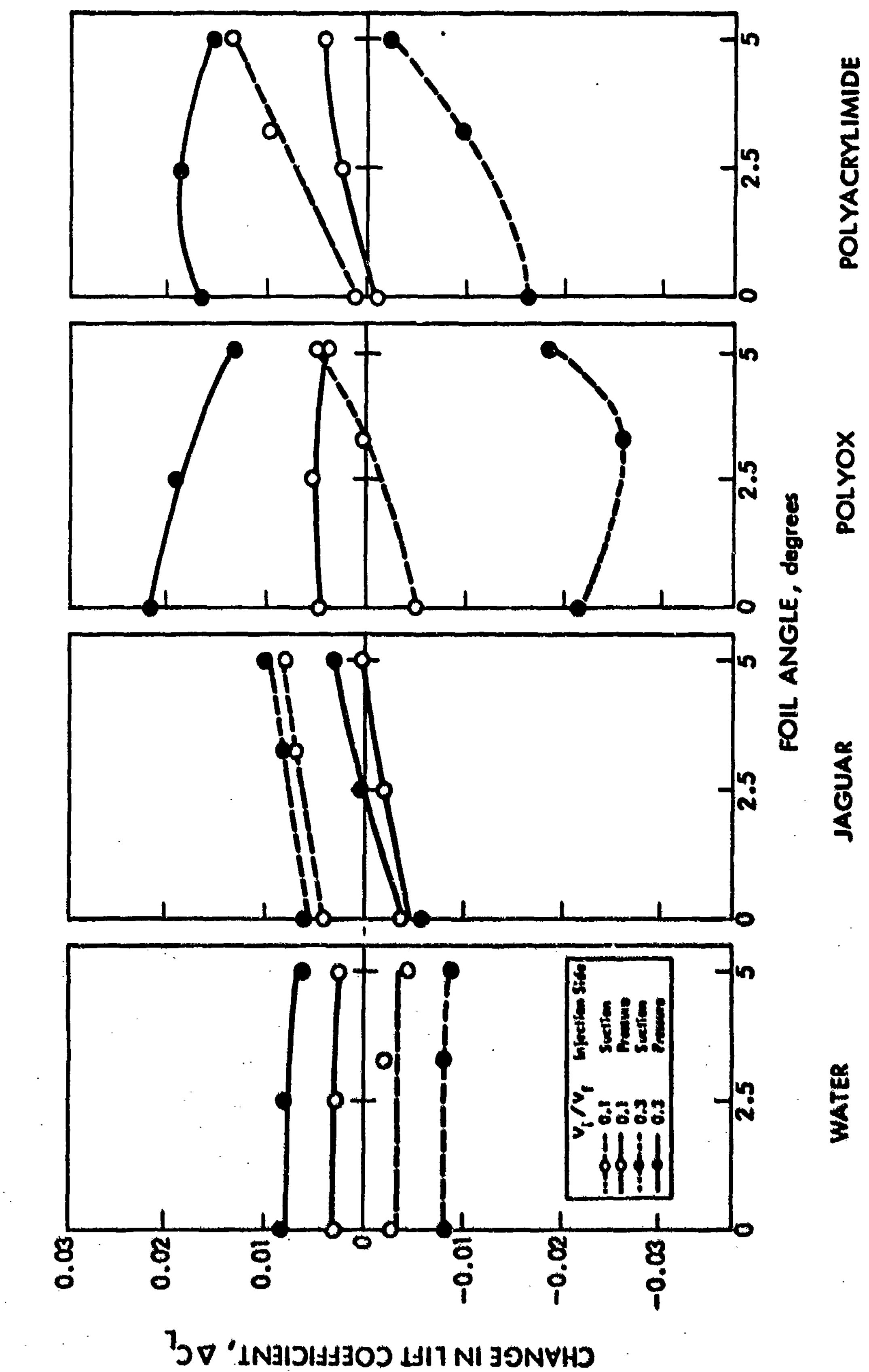

FIGURE 9 - EFFECT OF 30% CHORD INJECTION OF WATER AND POLYMERS ON THE LIFT COEFFICIENT OF A 10 cm CHORD HYDROFOIL

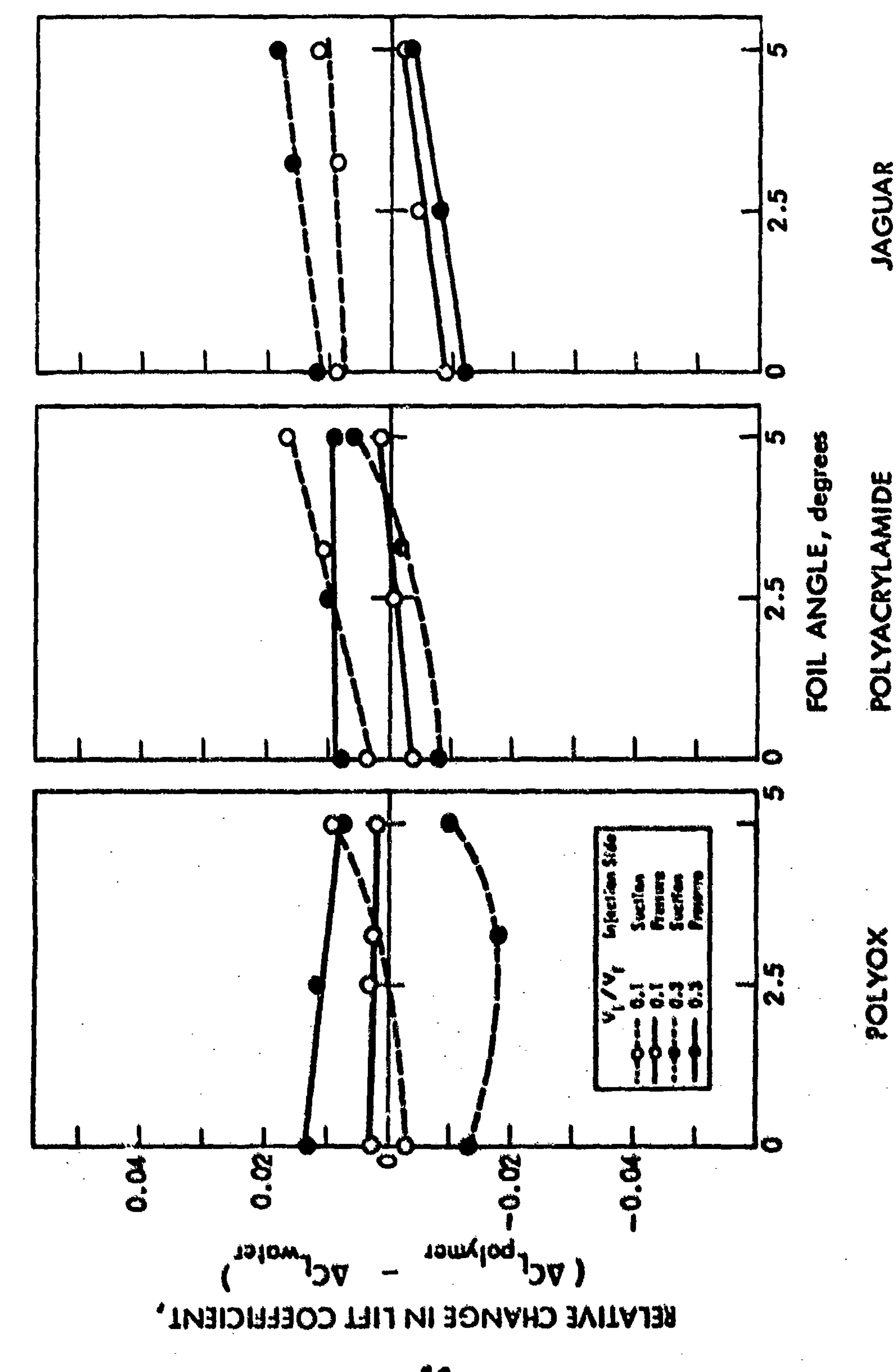

FIGURE 10 - EFFECT OF 30% CHORD INJECTION OF POLYMERS (RELATIVE TO THAT OF WATER) ON THE LIFT COEFFICIENT OF A 10 cm CHORD HYDROFOIL

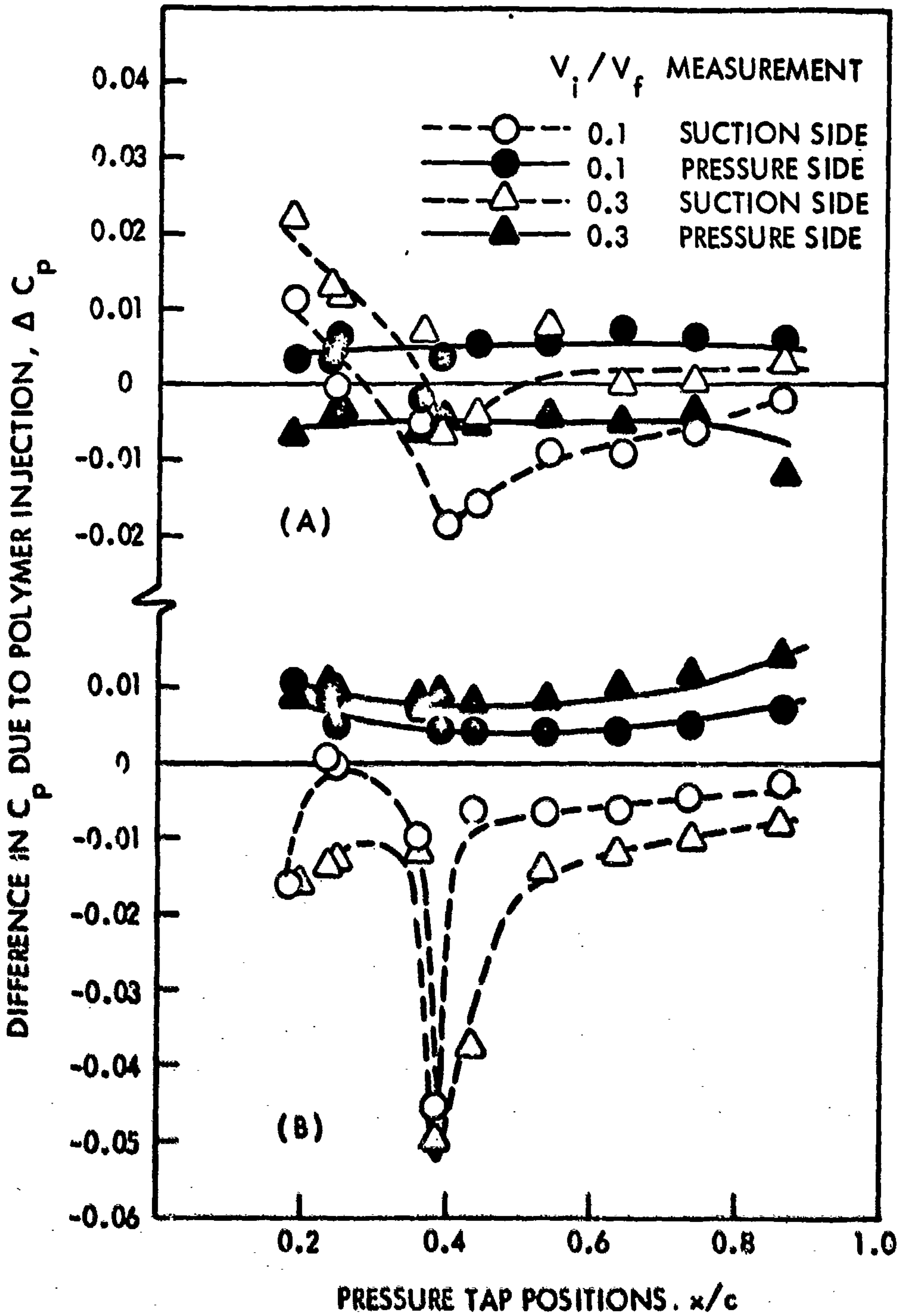

FIGURE 11- EFFECT OF 10% CHORD SUCTION SIDE INJECTION OF (A) POLYOX AND (B) JAGUAR ON THE PRESSURE DISTRIBUTION OF A 10 cm CHORD HYDROFOIL AT FOIL ANGLE OF 2.5 DEGREES

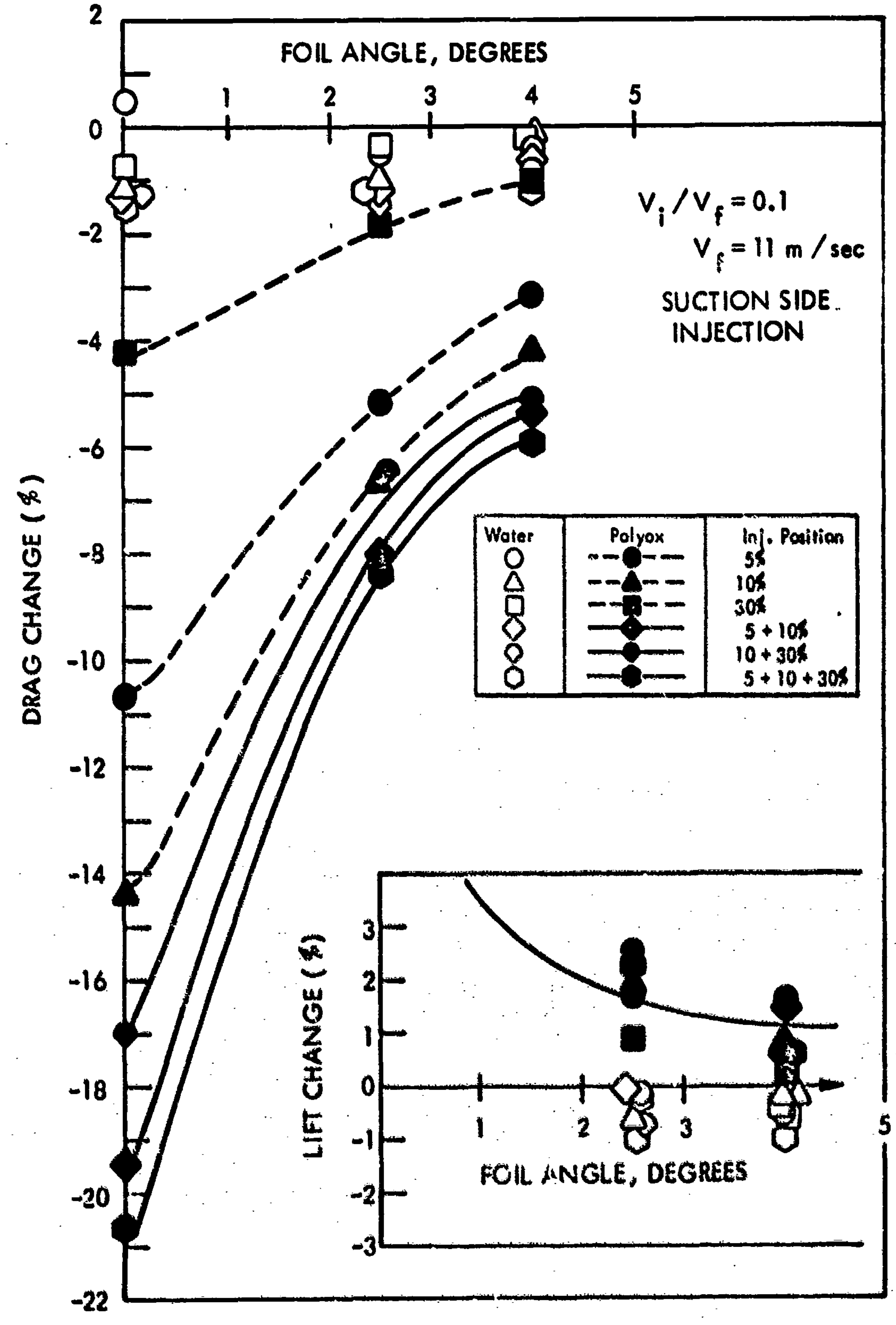

FIGURE 12 - EFFECT OF WATER AND POLYOX INJECTION THROUGH VARIOUS COMBINATIONS OF INJECTION POSTIONS ON THE LIFT AND DRAG OF A 20 cm CHORD HYDROFOIL

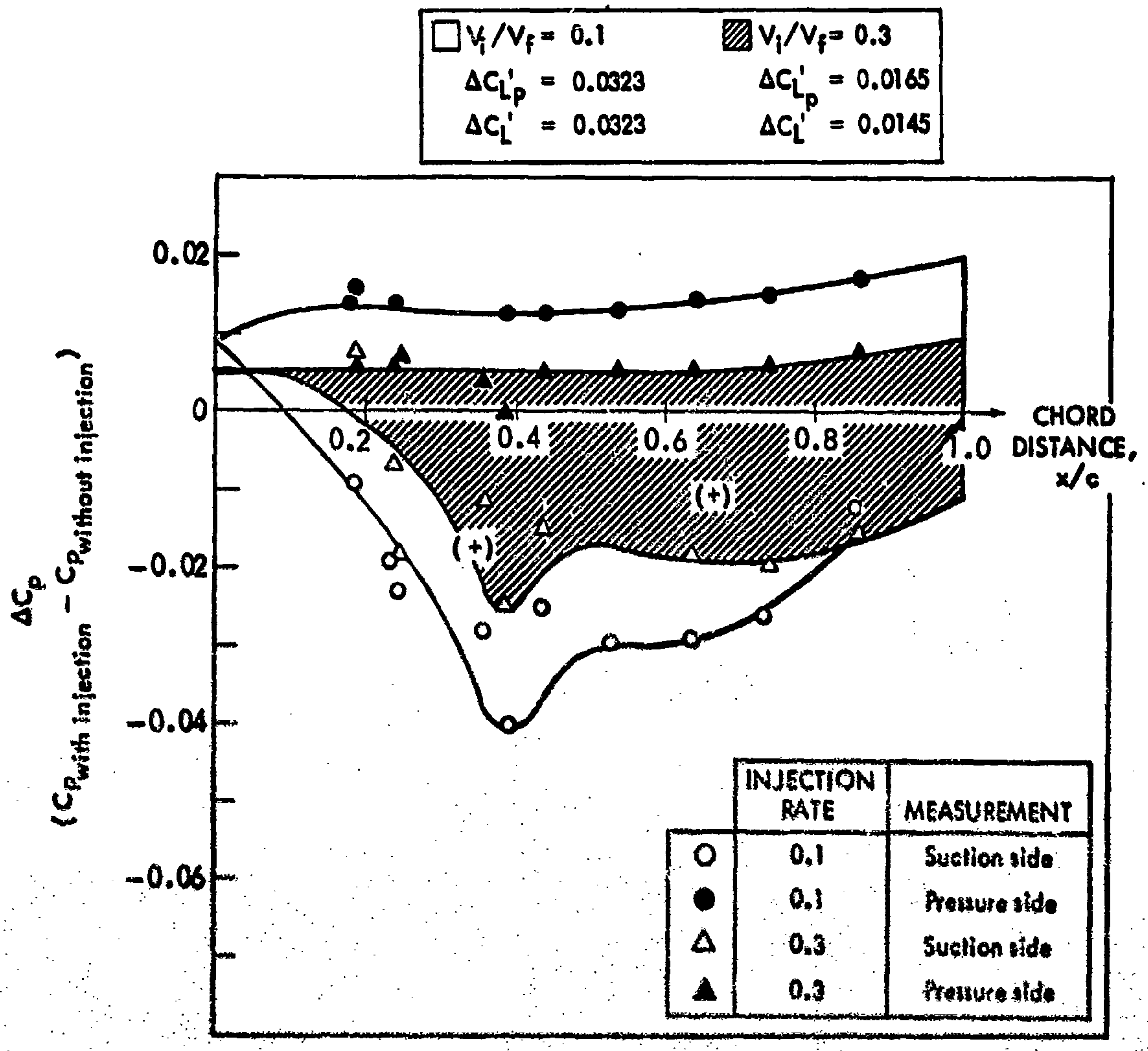

FIGURE 13 – CHANGE IN THE PRESSURE DISTRIBUTION AROUND THE 10 cm CHORD HYDROFOIL; α = 5° ; 10% CHORD SUCTION SIDE INJECTION OF POLYOX

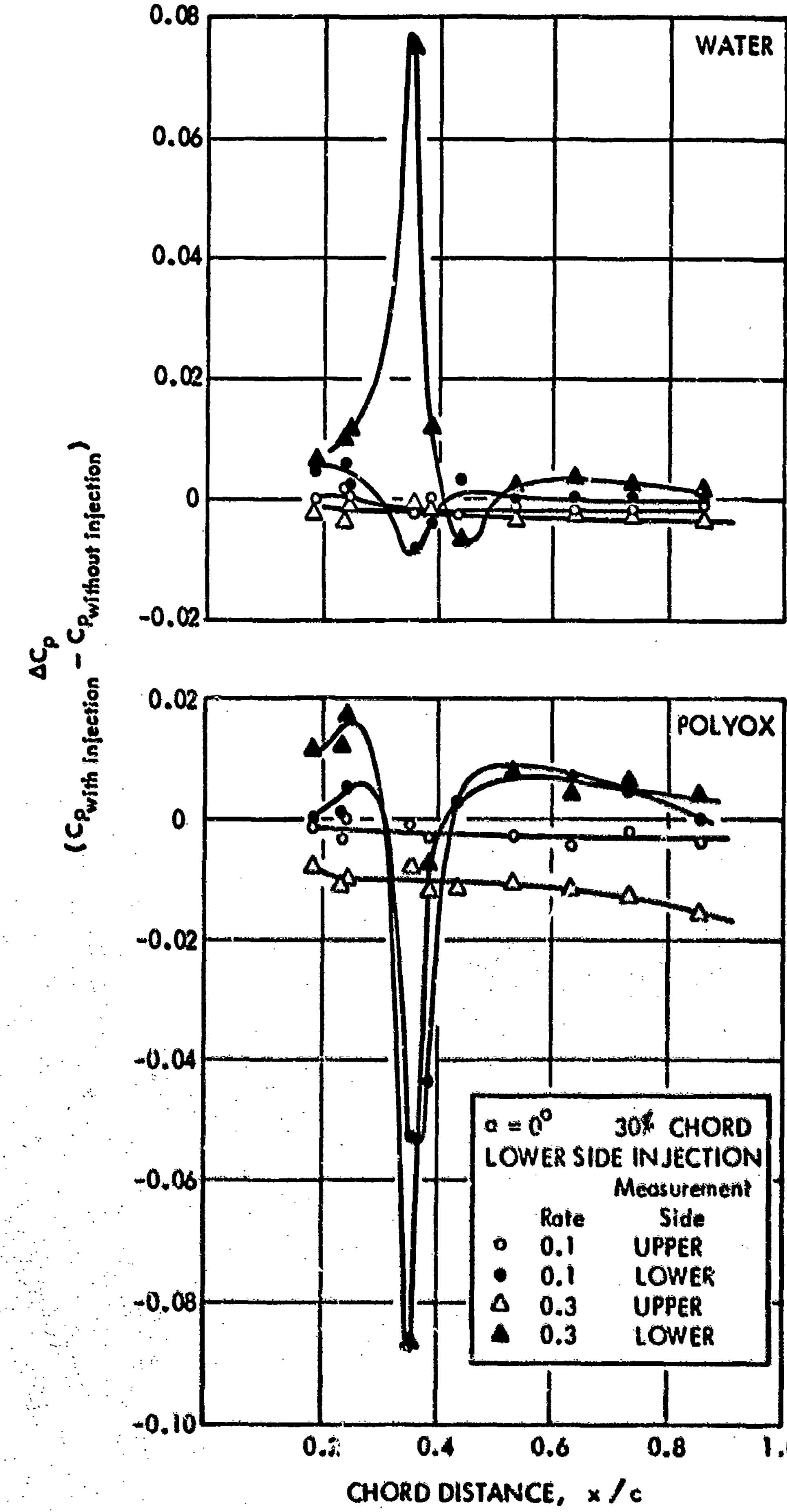

FIGURE 14- DIFFERENCE IN PRESSURE COEFFICIENT, ΔC_p VERSUS CHORD DISTANCE, x / c